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James R. Andrews, et al

Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THE DEVELOPMENT OF AN OPTICALLY ACTIVE LASER SCHLIEREN SYSTEM WITH APPLICATION TO HIGH PRESSURE SOLID PROPELLANT COMBUSTION

by

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A laser schlieren system, using an optically active quartz prism-polaroid sheet combination aperture in place of the conventional knife edge, was developed and applied to high pressure solid propellant combustion studies. Advantages and limitations of the system are discussed. Ammonium perchlorate deflagration was observed to pressures of 2200 psi. Distinct surface reaction sites were evidenced at high and low pressures by alternating density gradients in the gas across the deflagrating surface. These sites were found to be very small or nonexistent at intermediate pressures.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Until the past several years, solid propellant developments were largely empirical processes due to the very limited understanding of propellant combustion mechanisms. Studies during the past two decades have been able to identify many propellant parameters and establish limited but useful models for the immensely complex phenomenon of solid propellant combustion. The development of adequate models is an obvious necessity for the more complete understanding of propellant combustion. In order to develop these models, however, carefully planned and controlled experiments are required in order to provide a realistic foundation.

Numerous optical techniques have been devised to gain insight into the dominant mechanisms in solid propellant deflagration. For example, high speed motion pictures, density field techniques (schlieren, etc.), selected absorption, electron microscopes, etc. have been used in recent years. Kubota and others used a combination of very fine (4 micron bead) thermocouples and high speed infra-red photography to study the site and mode of action of platonizers in double base propellants (Ref. 1). Murphy and Netzer (Ref. 2) used a mercury arc source schlieren system for AP and AP-Binder sandwich combustion studies. Klahr and Netzer (Ref. 3) further attempted the use of an agron (CW) laser source schlieren with either a neutral density wedge filter or a knife edge to study a variety of solid propellant combustion. Developments in laser light source optical systems, including schlieren, have been reported by Lu (Ref. 4) and Oppenheim (Ref. 5). These systems are potentially valuable tools for propellant combustion studies. A combination of high speed photography (with other than laser light sources) and/or detailed surface study of thermally or

depressurized quenched ssmples with a scanning electron microscope have been reported by a number of researchers including Boggs (Ref. 6), Boggs and Kraeutle (Ref. 7), Derr and Boggs (Ref. 8), Boggs snd Zurn (Ref. 9), Hightower and Price (Ref. 10), Varney and Strahle (Ref. 11), and Strahle, Handley and Kumar (Ref. 12).

Using an opticsl system of some type to study propellant combustion in a high pressure atmosphere provides a unique opportunity for a "stop action" observation as well as continuous slow motion study of the flow field and surface configuration. Furthur, a well designed optical scheme has little effect on the combustion mechanism. This is particularly important when the boundsry conditions are significant as is the case when samples sre tested in small pressure vessels. Although highly attractive, particularly from a qualitative analysis standpoint, optical systems have several disadvantages when applied to combustion studies. The problems tend to fall into two areas: problems associated with the combustion system or mechanism itself and those associated with the optics system, independent of any particular item in the test section.

Combustion products, particularly smoke, accumulating within the combustion bomb or immediately above the burning surface can scatter or absorb light and generally obscure the surface action as well as degrade schlieren observations. Too low s purge rate allows too much smoke to accumulate while purging too rapidly might cause a large convective heat loss, thus affecting the combustion mechanism itself.

A major problem in observing surface behavior and the gas phase just above the surface during high pressure combustion of certain propellants is the visible light or self-luminous interference effects from the combustion zone. As the pressure is raised, the combustion zone tends to move closer to the solid

surface and the problem is magnified. This interference overpowers schlieren observations resulting in a yellow overtone in color photography or a washed out region in black-and-white (Refs. 3 and 4). With an unlimited light source power supply, it is conceptually possible to simply overpower the interference but at the potential risk of effecting the combustion mechanism if the source intensity is high enough to cause heating of the specimen or the flow. A second and preferable potential solution is the use of the monochromatic properties of laser light and a narrow-pass filter with the filter at peak transmission at the laser wavelength (Ref. 4). The wavelength of the laser and filter should be significantly displaced from the expected peak of the self-luminous interference.

In order to create a controlled steady state high pressure environment, a secure pressure vessel complete with viewing ports, ignition system and exhaust/purge facilities is required. The optical quality of the vessel windows must necessarily be high, particularly for a laser light source, and their physical strength sufficient to withstand the intended pressures. The internal dimensions of the chamber must be sufficient so as not to constitute an adverse boundary condition and unduly influence burning. The possibility for equipment failing under high pressure operation imposes additional safety precautions such as a remote control console from which the experimental runs may be initiated.

The techniques of ignition must include a minimum interference effect on the combustion mechanism. It is possible to create a heat sink if the specimen mounts or ignition system members are too massive or too close to the specimen, thus altering the burning. It is also highly desirable to have as even ignition as possible across the surface of the specimen.

Motion picture systems for data recording offer the possibility for both "stop action" as well as slow motion study of the flow field without interfering with the combustion process. Other methods, such as quenching, may actively interfere with the process while Q-switching laser techniques do not provide for continuous observation. Probes or fine wire thermocouples are also used but must be precisely positioned and represent a possible discontinuity during the burn. For motion picture recording, the light source must be of sufficient power for the desired beam geometry to enable film exposure at the necessarily high framing rates. The power levels for Q-switching techniques present no problems but for CW lasers in the visible spectrum the power levels are limited and the efficiencies low. The losses from each member of the optics train must also be considered in order to yield the necessary light intensity at the film plane. High ASA ratings for high speed films and developing methods to extend the ASA ratings may assist for lower light levels. Due to the time required for the camera to accelerate the film from rest to the selected framing rate, it is essential that the ignition and camera initiation be fully coordinated to account for the propellant burn time at the selected pressure and the available film length. This generally necessitates some method of viewing the specimen from the remote control console.

The test section for high pressure combustion studies is defined by the internal dimensions of the pressure vessel. The objective in the schlieren approach is to observe density gradients in a single plane and usually in a single direction. The flow field, however, is three-dimensional and the axial thickness of the field results in an averaging effect over the thickness of the test section.

The specimen has a known finite thickness in the viewing direction. Depending on the criticality of focus, some reference point definition is required The thickness variation of the gas phase with height above the burning surface should be considered in focus point definition. Simultaneous good focus of both the solid and gas phases, as well as obtaining the desired magnification, can be a major problem.

Interaction of coherent monochromatic laser light with the conventional knife edge produces diffration patterns which render this combination unsuitable for laser schlieren systems (Ref. 4 and 5). The inherent fringing around the periphery and general inhomogeniety of the laser beam may require it to be "cleaned" by spatial filtering or other techniques in order to be suitable for use in a schlieren system. Unmodified laser beams and the benefits of spatial filtering are discussed and illustrated by Klein (Ref. 13).

The plane polarized characteristic of laser light allows the use of optically active crystals to replace the conventional knife edge and thus to minimize or eliminate the associated diffraction patterns. The major advantage, however, of an optically active aperture is derived from the monochromatic nature of laser light which permits the use of a narrow-pass filter to minimize or eliminate the problem of aelf-luminous interference with the schlieren. An additional advantage of a laser source is the dual use with a hologram setup or other dual system as reported by Lu (Ref. 4).

The major objective of this study was to develop a laser schlieren (optically active aperture) system designed to eliminate the problem of self-luminous interference during flow field studies and to apply it to the study of combustion of certain propellants to pressurea of 2200 psi.

II. EXPERIMENTAL APPARATUS AND PROCEDURES

A) Apparatus and Theory of Operation

1. Optical Activity

The optical system employed in this study consisted of a CW argon laser schlieren using high quality lenses, an optically active aperture in place of the conventional knife edge, and a bi-concave lens to initially diverge the laser beam.

The schlieren aperture used was an optically active 30 degree single-crystal quartz prism combined with a polaroid sheet. The commonly accepted theory of optical activity and optically active materials has been attributed to Fresnel (1825) and may be found fully described in Refs. 14-19. Very briefly, optical activity is the phenomenon displayed by certain crystals and solutions which rotate the plane of vibration of polarized light. The fundamental cause of optical activity in crystals is the atomic arrangement in like-handed spirals along the direction of propagation of the light. This direction is known as the optically active axis. The amount of rotation depends on the optically active material, ie. quartz, cinnabar etc., the wavelength of the light and, to a smaller degree, the temperature. The crystalline structure of quartz (silicone dioxide) has been described by Bragg and Claringbull (Ref. 20).

Data collected (Refs. 14, 15, 17, 19 and 21) indicate that the amount of rotation by optically active quartz is strongly dependent on the wavelength and linear with distance along the optical axis. That is, given the wavelength and temperature, the specific rotation (degrees/mm) is a constant. A summary of the data in the references cited may be found in Table 1. A polynomial fit

was made to the data and is presented in Figure 1.

Over the visible range, from approximately 4000-7000 A, the following polynomial gives an excellent fit with errors of 1.30 deg./mm or less:

$$\phi_{\epsilon} \cong - 2.10 + 8.14 \times 10^{8} / \lambda^{2} \qquad (1)$$

2. Apparatus

Parallel rays passing through a flow field with density gradients are differentially refracted resulting in a shift of position of impingment on the perpendicular face of the quartz prism. The displaced light travels through differing thicknesses of quartz, which in turn rotates the plane of polarization by differing amounts. The polaroid acts as a filter to pass rays whose rotation is close to the polaroid orientation and absorb the others. In order to avoid the deflection of the entire beam after passing through the quartz prism, a second complimentary but optically neutral prism of matching index of refraction is necessary (Refs. 4 and 5). Figures 2 and 3 show the geometric relations of displacement to rotation and the qualitative ray tracing through the prism system.

The completed optical system is shown in Figs. 4 and 5. The laser source beam was diverged by a bi-concave lens to the desired diameter at the first schlieren lens. The focal points of the first schlieren lens and bi-concave lens were coincident. The first schlieren lens collimated the beam and directed it through the test section, the narrow-pass filter and on toward the second schlieren lens. The second schlieren lens focused the quasi-parallel beam from the test section to a point in a plane coincident with the perpendicular face of the single-piece quartz crystal. The light passed through the quartz prism and correcting prism, through the polaroid sheet and was focused onto the film

plane by the final focusing lens.

The light source used wss a Control Laser continuous wave (CW) argon laser, model 902A, operating st the 4800 A line. The laser was operated at 32 AMPS/220 VAC to deliver a power of 1.3 watts.

The positioning of the two schlieren lens and the final focusing lens was determined from lsborstory space considerations and the final imsge size desired on the film plane. The physical size limitations of the laboratory would have forced "folding" the optics seversl times if a real imsge system were to be used. In order to shorten the optics and still achieve the desired final image size near 1.0 magnification, the second schlieren lens was placed such that the test section was inside its focal point. The virtual image thus created by the second schlieren lens wss used as the object for the final focusing lens. Figs. 6 and 7 show the approximate layouts for the real and virtual image systems for a final magnificstion of near unity based on thin lens assumptions.

All photographic records were made directly onto the film plane. The omission of the csmera lenses reduced the complexity of the optical problem and minimized furthur light losses. Initisl system evaluation was done by taking long exposure schlieren pictures of laminar flames. They were made using a Leica (model M-2) camera and TRI-X 135 Panchromatic film (ASA 400). Exposure times of 2 milliseconds produced satisfactory results. For motion picture recording, a Hycam Model K2004E-115 high speed 16mm motion picture camera was used. Framing rates of up to 10,000 frames/second were used with exposure times of 80 microseconds or less depending on the associated shutter used. The lower limiting time capability was 1 microsecond. Movie film types included 7277 4X reversal (ASA 400), 2475 Estar-AH base (ASA 1000) and 7224 negative (ASA 500). The 7277 4X was primarily used because it hss a color

sensitivity peak in the blue-green. A Red Lake Millimite TLG-4 timing oscillator was used during all movie runs to provide a time mark on the film edge at pre-selected time intervals.

The narrow-pass filter was located immediately downstream of the test section, prior to the second schlieren lens.

Either of two pressure vessels could be used. Each combustion bomb was connected to a common ignition system as well as common plumbing for the nitrogen pressurization source and smoke purging system.

The low pressure bomb, Fig 8a, was made from 300-series bar stock steel with an internal test section diameter of 8.0cm. Photographic viewing ports 2.54cm in diameter and oriented along the axis were fitted with plate glass windows 3.2cm thick. An additional viewing port was located on the side of the bomb for ignition-camera initiation coordination. The low pressure bomb was pressure tested to 1500 psi but limited to operation at 800 psi.

The high pressure bomb, Fig. 8b, was fabricated from 347 bar stock steel and likewise fitted with two viewing ports along the axis and one on the side. The internal test section diameter was 5.0cm. Due to the maximum operating pressures of 3000 psi, the viewing diameter was reduced to 1.27cm and the windows were made from schlieren quality neutral quartz 3.2cm thick. The high pressure bomb was pressure tested to 4500 psi prior to any experimental runs. As an added safety precaution for the very high pressures, a steel shroud was fitted to surround the entire bomb.

To accomodate the change of window diameter between the two bombs and to achieve as little light loss as possible, two bi-concave lenses were used as follows: 5.0cm focal length lens for the low pr[illegible]e bomb to give a test section beam diameter of approximately 2.6cm; 10.0cm focal length lens for the

high pressure bomb with a beam diameter of about 1.3cm.

The remote control console provided for complete control of system pressurization, ignition and camera initiation. A surveyor's transit and first-surface mirror provided pre-ignition observation of the specimen for camera coordination.

The ignition system consisted of two electrodes mounted on either side of the specimen pedestal (see Fig. 9). Between the electrodes a #32 nickel-chromium wire was pulled taut across the upper specimen edge and secured to each side. The ignition wire was electrically in series with a variable resistor in order to control the current provided by the 12VDC battery source. A continuity check circuit was also included.

The pressurization/purge system was controlled from the remote console through a dome valve. This dome valve in turn controlled the flow from the compressed gas reservoir, nitrogen in this case. A pressure tap and gage were used to observe the bomb pressure. Exhaust port valves on the top of the bomb controlled the rate of the exhaust flow for smoke removal. The N_2 purge gas was introduced through a porous plate in the bottom of the chamber, passed up through the test section and then vented to the atmosphere.

3. Schlieren Sensitivity

The sensitivity of any schlieren system is a function of the focal length of the second schlieren lens/mirror and the type and adjustment of the aperture. The conventional knife edge system has been described by Leipmann and Roshko (Ref. 22).

Collimated light, passing through the test section, is refracted by spatial and temporal fluctuations in the index of refraction. Light is refracted toward an increasing density (positive density gradient). The density field which

causes the index of refraction fluctuations is the result of the combustion physics of a given propellant under a specified pressure. In addition, effects from the exhaust system flow could be superimposed on the density field if the flow were too high. The total refraction of an individual ray of light is the sum of all incremental effects from entry to exit of the test section. Specifying the test parameters (ie. propellant type, pressure, etc.) fixes the resultant total refraction. Thus, the net refraction is not available as a parameter for sensitivity or contrast control in the schlieren record. The more sensitive the schlieren system, the smaller the total refraction can be and still produce a detectable schlieren record.

The second schlieren lens/mirror focuses the quasi-collimated light from the test section to a point at the schlieren aperture. Refracted light rays are displaced at the aperture relative to unrefracted or reference rays by an amount proportional to the total refraction, ε , and the focal length of the second lens, f_2 (Fig. 2). The displacement, $\Delta X = f_2\varepsilon$, is directly related to sensitivity. The second lens can degrade the schlieren quality through spherical aberrations if too small in diameter or if the beam is well off center. Non-uniformities in the glass may also degrade the resultant schlieren record.

The optically active aperture (quartz prism-polaroid) previously described controls both sensitivity and contrast, assuming a fixed total refraction, ε , and a specified focal length, f_2. With any combination of system optical members included, assuming the laser polarization is not destroyed, polaroid orientation will determine the darkness of the "neutral" background and the light-dark extremes possible in the schlieren record. It is possible to observe identical schlieren records for differing total refractions (density

gradients). That is to say, there is a certain cyclic nature or periodicity associated with this schlieren aperture. The nature of the periodicity is dependent on the total system sensitivity and the relationship of reference ray polarization orientation to that of the polaroid sheet transmission axis.

The polaroid sheet has an axis of maximum transmission and, 90 degrees to it, an axis of maximum absorption. In general, the polarization orientation of the reference (or unrefracted) rays, after having passed through the prisms, should bisect the two axes of the polaroid sheet (Fig. 10(a)). The reference could be along either bisecting axis. Ideally, the steepest density gradients in the flow field, coupled with the total system sensitivity, should cause a maximum differential rotation of ±45 degrees for the refracted rays. This would correspond to the extremes of the light-dark and produce the optimum schlieren record. With the reference polarization as shown in Fig. 10(a), increasing the sensitivity would cause a greater rotation for the same density gradients. If the deflected portion of the beam is rotated more than ±45, an erroneous reversal in the density gradient would be indicated. This cyclic behavior becomes more critical in one direction if the reference axis and polaroid transmission axis are at other than 45 (Fig. 10(b)). This is sometimes necessary when a darker schlieren record is required.

In the present investigation, approximate calculations of the system sensitivity indicated that less than 10 degrees of rotation could be expected for typical free jet diffusion flames.

4. Vertical Smearing of the Schlieren

During the exposure time for any given frame, the hot gases have a vertical velocity which results in a "smearing" on the film. The smear is simply the distance a "gas particle" may move during the exposure time. Approximate calculations for ammonium perchlorate deflagration at 500 psia indicated that a smear of about 0.001 inches could be expected using the filming methods discussed above.

B) Experimental Procedures

1. Introduction

The first phase of the investigation was for initial system setup, familiarization and development. Items such as city gas diffusion flames, candle flames and premixed flames were used at atmospheric pressure for basic quality and sensitivity comparisons with previously reported systems. Initial results showed enough potential to continue with the second phase.

The second phase of the test plan was to duplicate portions of the solid propellant combustion study reported by Murphy and Netzer (Ref. 2) and Abraham, Klahr, Gerhardt and Netzer (Ref. 3) for direct comparison of sensitivity, quality and feasibility using identical specimens and environments.

The final phase was to apply the system to combustion phenomena which could not be readily studied using conventional schlieren techniques. More specifically, ammonium perchlorate deflagration was examined to pressures of 2200 psi.

2. Initial System Setup

The CW argon laser was tuned to 4800 A using the combination of an optical power meter and the characteristic blue-green color. 4800 A and 5145 A were the two primary lines (for maximum power) of the laser. The 4800 A line and matched narrow-pass filter combination was specifically selected to move as far as possible in the electromagnetic spectrum from the expected wavelengths of 5100+ A for self-luminous interference. Other laser lines below 4800 A did not provide sufficient power to be considered.

System focus proved, initially, to be a problem and overall to be critical for reasonable resolution. The final focal plane was identified relative to

the reference of the final focusing lens. A small white screen was used to observe the focus of a fine wire loop in the center of the test section. The specimen magnification in the final focal plane was approximately 0.85.

Initially a spatial filter was used to "clean" and diverge the beam prior to the first schlieren lens. In this arrangement, the pinhole plane was located at the focal point of the first lens. The combination of power losses across the filter itself and the large divergence angle made it impossible to expose the film (7277 4X reversal ASA-400) at or above 2000 frames per second. A satisfactory substitution was found using a bi-concave lens prior to the first schlieren lens with the two focal points coincident. The bi-concave focal length coupled with that of the first schlieren lens controlled the beam geometry at the first lens and, consequently, through the test section as indicated in Fig. 11. By minor adjustments of lens L1A, a useable portion of the beam could be placed on the propellant specimen without furthur beam filtering.

Tuning the system to the best schlieren response was largely a matter of finesse and involved adjusting the combination of quartz prism and polaroid. Initially, the polaroid was adjusted (without the prisms or bomb windows in place but all other optical elements included) for about 50% transmission. The prisms, mounted on a two-degree-of-freedom micrometer stage, were moved into place and fine adjusted until the desired schlieren contrast was produced. If the background changed and became too light or too dark the polaroid was rotated slightly to a position of more or less transmission and the prism readjusted to obtain satisfactory schlieren. This tuning continued until the combination of good background and good schlieren were simultaneously produced. A good background was as uniform as possible with the transmission level about

half way between the light and dark schlieren extremes. Prior to each combustion bomb run, the system was "tuned" using the laminar portion of a city gas diffusion flame.

3. Specimen Preparation and Mounting

A variety of specimens were used including ammonium perchlorate, both single crystal ultra-high purity (SC-UHP) and polycrystalline (PC-UHP), ammonium perchlorate-binder sandwiches and a solid propellant which utilized large unimodal AP. Sizes and construction techniques were similar to those reported by Netzer, et al. (Refs. 2 and 3), Boggs (Ref. 6) and Strahle (Ref. 12). The specimens were mounted on end on small pedistal supports designed to fit into a a test section holder. The ignition wire was stretched across the top edge of the specimen as shown in Fig. 9. For sandwich burners and composite propellants, a small amount of a mixture of black powder, glue and acetone was spread on the top of the wire and upper edge. This assisted in a flash ignition across the entire edge and contributed to an even regression across the width. A surveyor's transit and first surface mirror provided observation and coordination of the ignition and camera initiation sequence.

III. RESULTS AND DISCUSSION

The photographic results showed that the self-luminous interference which occurs for solid propellant combustion was eliminated by using the narrow-pass filter. In genersl, the results were in good agreement with the previously reported results of Murphy and Netzer (Ref. 2) and Klahr and Netzer (Ref. 3). Some disadvantages were identified which prevent this type optical system from also being readily used for detailed surface structure ohservstions. The basic feasibility, nonetheless, of application of an optically active aperture laser schlieren system to high pressure solid propellant combustion research was demonstrsted.

A schlieren photograph of the laminsr portion of a city gas diffusion flame is shown in Fig. 12(a). Although the quality is somewhst reduced, this schlieren record is in agreement with photographs provided by Gaydon and Wolfhard (Ref. 23). The laminar jet at the center of the flow is clearly identifiable. Note the laser light diffractions along the solid boundaries of the small gas tube, the larger solid propellant specimen support and around the curved boundsry defined by the narrow-pass filter. In addition to the diffractions along solid boundsries, laser light is also extremely critical of any optical anomaly in the system. Although high quality optic members were used, several small defects were identified under laser illumination.

A schlieren photograph of a candle flame is shown in Fig. 12(b). The ascending hydrocsrbon vapor can be seen surrounding the wick.

The still picture results for candles and gas diffusion flames were, in general, of lower quality and sensitivity than for conventional schlieren systems. There are at least three major contributing reasons: peculiar

properties of the laser light itself (ie. solid boundary diffractions, etc.), limited schlieren light-dark extremes available due to the transmission and absorption properties of the polaroid (40-70% transmission) and the limited total sensitivity of the reported system. Since these constant pressure diffusion flames were not intended as the major area of application of this schlieren system, no effort was made to match density gradients and total system sensitivity as previously discussed.

The reduction or elimination of self-luminous interference, particularly yellow light, was a primary objective of this optical system development. Initially, results using 7277 4X reversal film indicated that the narrow-pass filter was effectively eliminating this interference from samples of AP/HTPB and AP/PBAA sandwich burners and N3 propellant (21% weight PBAN binder with 79% weight unimodal AP from 420-500 μ). The final check for filtering affect on self-luminous interference was made using an AP/PBAA sandwich (binder thickness 406 μ) and 7242 ektachrome color film. The specimen was visually observed to be highly self-luminous during the burn. Fig. 13 shows the effective narrow-pass filter elimination of this interference.

Fig. 14 shows selected frames from 7277 4X high-speed motion pictures of ammonium perchlorate (AP) burning at various pressures. As measured from Fig. 14(b), the resolution limit for the system, based on fringing, was approximately 60 μ. All exposure times for Fig. 14 were 80 μsec.

Fig. 14(a) shows a single-crystal ultra-high purity ammonium perchlorate specimen (AP-SC-UHP) 4.7mm wide burning at 500 psi. The results were in good agreement with the color schlieren of Murphy and Netzer (Ref. 2). Individual surface reaction sites were observed (as evidenced from the gas phase density gradients) to be distributed rather evenly across the surface. The sites

appesred to be on the order of 180-280 μ in width, slightly smaller than reported by Netzer and Murphy (Ref. 2). The deflagration appeared to be laminar. The definite temperature pesk above the center of the specimen, as reported by Murphy and Netzer was not observed.

Fig. 14(b) shows a pressed polycrystalline ammonium perchlorate specimen (PP-UHP-AP) 4.83mm wide and 1.27mm thick burning at 450 psi. All (PP-UHP-AP) specimens were pressed at 30,500 psi for 20 minutes as described in Ref. 2. The light-dark schlieren shifts (evidence of individual surface reaction sites) appeared to be spaced 280-300 μ across the surface with large scale turbulence beginning about 500-600 μ above the surface. The front surface of the solid phase sppears dark due to the back lighting of the opaque specimen. Surface definition was poor in the interface region between the dark schlieren and the solid phase surface. Observable from the motion pictures was a "dancing" or apparent motion of the solid phase surface just below the burning surface. This was attributed to the reflections from the downstream bomb window. In the SC-UHP-AP specimen, this "dancing" was not observed since the transparent crystal allowed laser light transmission which overpowered any such reflections.

Smoke absorption appeared to be a major problem, particularly with the limited power laser light source. Light absorption by the smoke resulted in a darkened area which was superimposed on any light-dark shift resulting from density gradients and confused the record interpretation. On the right hand edge of Fig. 14(b), the smoke was evidenced by the gray region in the gas phase. Smoke accumulation was minimized by controlled purge rate.

Fig. 14(c) shows a PP-UHP-AP specimen 6.1mm wide and 1.27mm thick burning at 1000 psi. Fringing, light absorption by the smoke and apparent solid phase surface motion ("dancing") were all observed. There were two major differences,

however, between the 1000 psi and the 500 psi results. The first was a near-constant periodic pulsing of the burning process. At regular intervals, a very thin layer of smoke would move upward from the immediate vicinity of the surface all along the width. This smoke layer was everywhere parallel to the surface locally, that is, it reflected the instantaneous surface contour. This result was similar to those reported by Murphy and Netzer (Ref. 2). They reported a "thermal pulsing" when their aperture was positioned to detect vertical vice horizontal density gradients. Boggs and Zurn (Ref. 24) similarily reported an accumulation and shedding of unreacted products on the surface of potassium-doped AP crystals leading to a "stop and go" burning characteristic. The second difference was the lack of light-dark schlieren shifts across and just above the surface. This indicated little or no density gradients (ie. approximately constant temperature) across the surface with uniform burning. Murphy and Netzer (Ref. 2) reported similar results with "almost uniform color in the gases just above the surface." These results imply that surface reaction sites are very small or non-existent at 1000 psi.

Fig. 14(d) shows a PP-UHP-AP specimen 6.1mm wide and 1.27mm thick burning at 2200 psi. The surface locally appeared to be non-uniform with large scale turbulence very close to the surface. Density gradients were observed which extended to the burning surface. However, the smoke and fringing near the surface prevented a consistent determination of the size of the surface reaction sites. The pulsing behavior observed at 1000 psi was not observed at 2200 psi.

IV. CONCLUSIONS

1. The basic feasibility of using an optically active aperture laser schlieren system for high pressure solid propellant combustion study was demonstrated.

2. The major advantage of this schlieren system over conventional schlieren systems is the elimination of self-luminous interference.

3. For applications where the self-luminous problem is nonexistent (ie. shock pattern studies, etc.) a CW laser schlieren in general would be inferior to conventional schlieren systems. Conventional color schlieren has the added advantage over this system in that schlieren effects can be more readily distinguished from variable light absorption by smoke.

4. System resolution was limited to approximately 60 μ primarily by fringing. The fringing could, perhaps, be minimized or eliminated by using a bonded prism set and mirrors in place of the lenses. Another method of improving the schlieren quality would be to increase system sensitivity by using a longer focal length schlieren and/or a greater quartz crystal angle. This would allow the use of a polaroid axis which would provide a darker background, thereby "darkening-out" the fringes so that they would not be seen on the film.

5. At 500 psi, AP deflagrated in a steady manner with a rather planar surface. Individual surface reaction sites were evidenced by density gradients in the gas phase across the surface. The gas flow from the deflagrating surface was very laminar.

6. At 1000 psi, AP continues to deflagrate with a planar surface but is pulsating in nature. Surface reaction sites, if existing at all, were very small.

7. At 2200 psi, the pulsating behavior was not observed and the surface was locally non-uniform. Local reaction sites were evident but the gas flow immediately above the surface was very turbulent making surface observation difficult.

TABLE I
Specific rotation of quarts

ϕ_s(deg/mm)	λ Å	ϕ_s	λ
201.9	2265	29.73	5086
153.9	2503	27.46	5270
95.0	3034	26.5	5351
72.45	3404	25.54	5461
50.98	3969	22.1	5890
48.95	4047	18.0	6438
47.4	4102	17.26	6563
42.37	4308	16.54	6708
41.55	4358	15.55	6867
35.6	4678	13.9	7281
32.75	4861	11.59	7948

(data from refs. 14-16, 19 & 21)

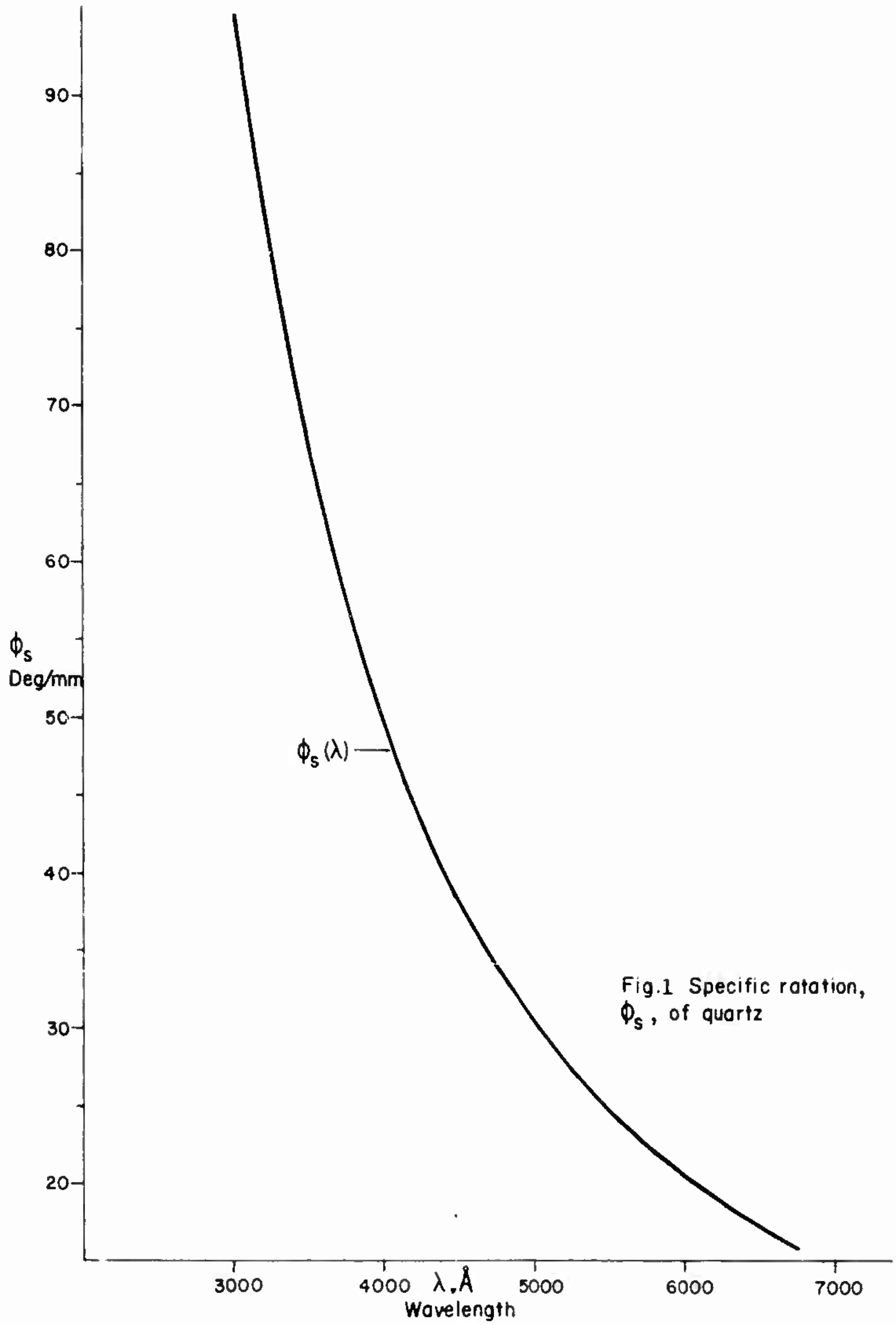
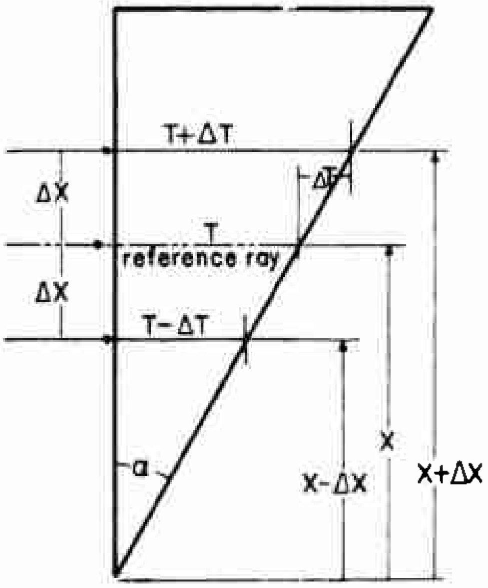


Fig.1 Specific rotation, ϕ_s, of quartz



$\Delta X = f_2 \epsilon$ - refraction displacement

$\Delta T = \tan(\alpha) \cdot \Delta X$ - diff. thickness

f_2 - focal length of second schlieren lens

ϵ - total refraction

Fig. 2 Geometric relationship of differential thickness, ΔT, to refraction displacement, ΔX

n - index of refraction

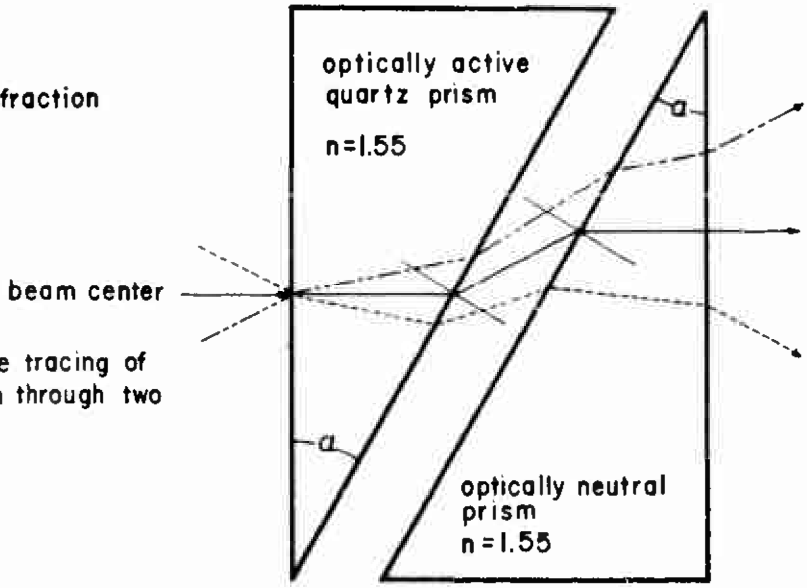


Fig.3 Qualitative tracing of converging beam through two prisms

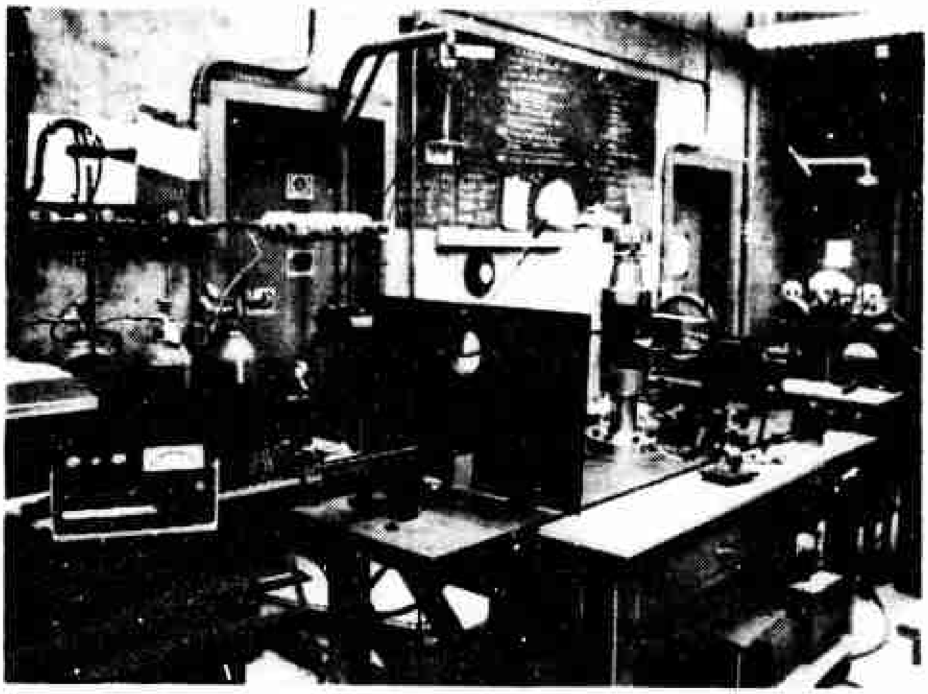


Fig 4a. General layout of schlieren system

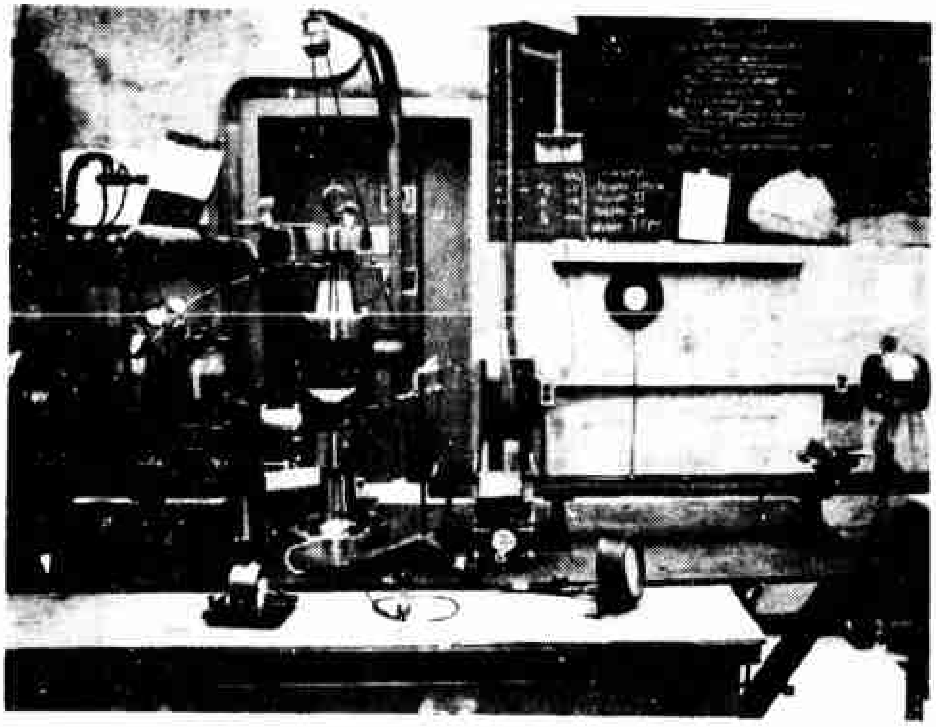


Fig 4b Side view of schlieren system from lens L_1 to lens L_3

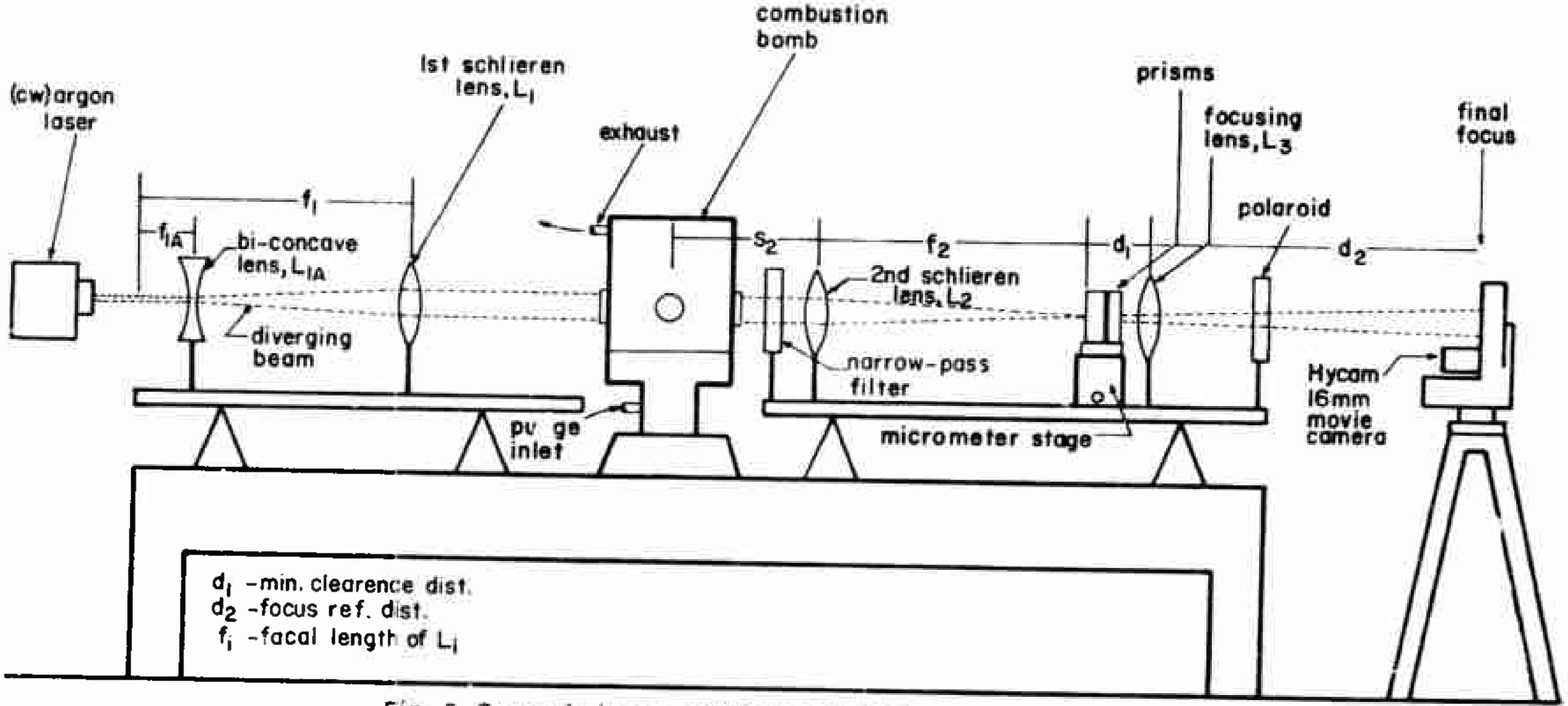


Fig. 5 General laser schlieren system
(side view)

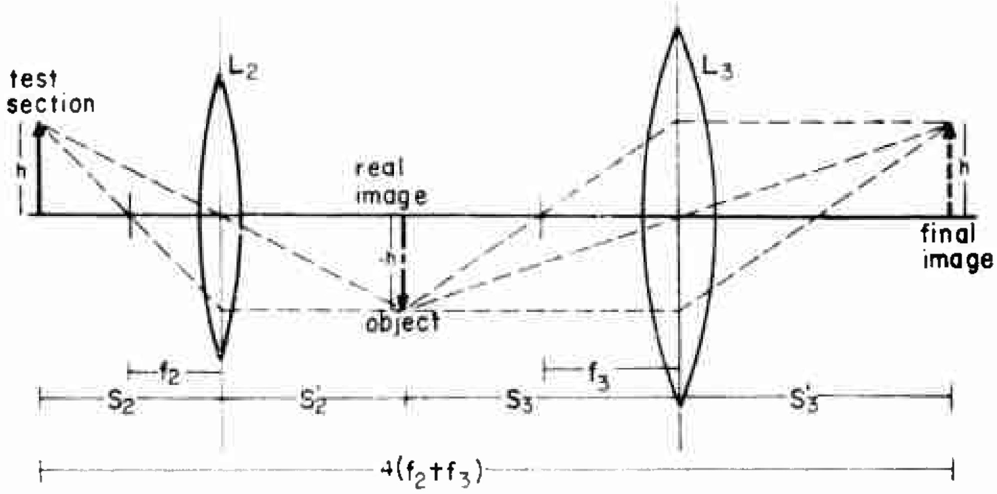


Fig. 6 Real image setup ($S_2 = 2f_2$ & $S_3 = 2f_3$)

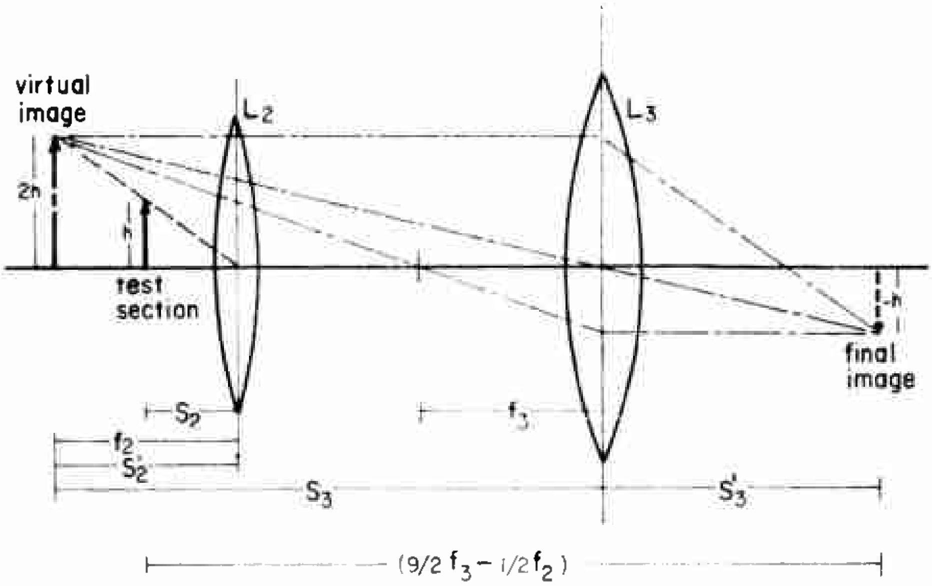


Fig. 7 Virtual image setup ($S_2 = 0.5\,f_2$ & $S_3 = 3f_3$)

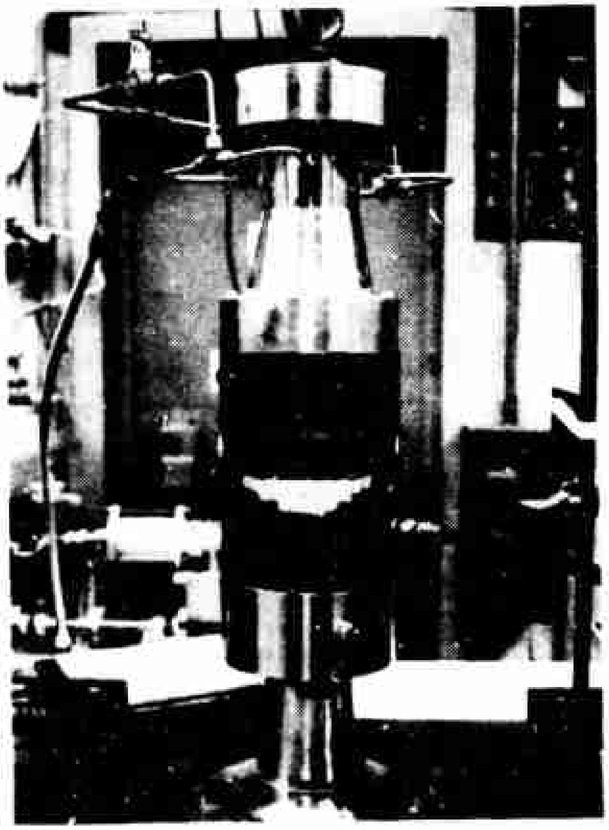


Fig. 8a Low pressure combustion bomb (800psi)

Fig. 8b High pressure combustion bomb (3000psi)

Fig.9 Typical specimen maunted for ignition

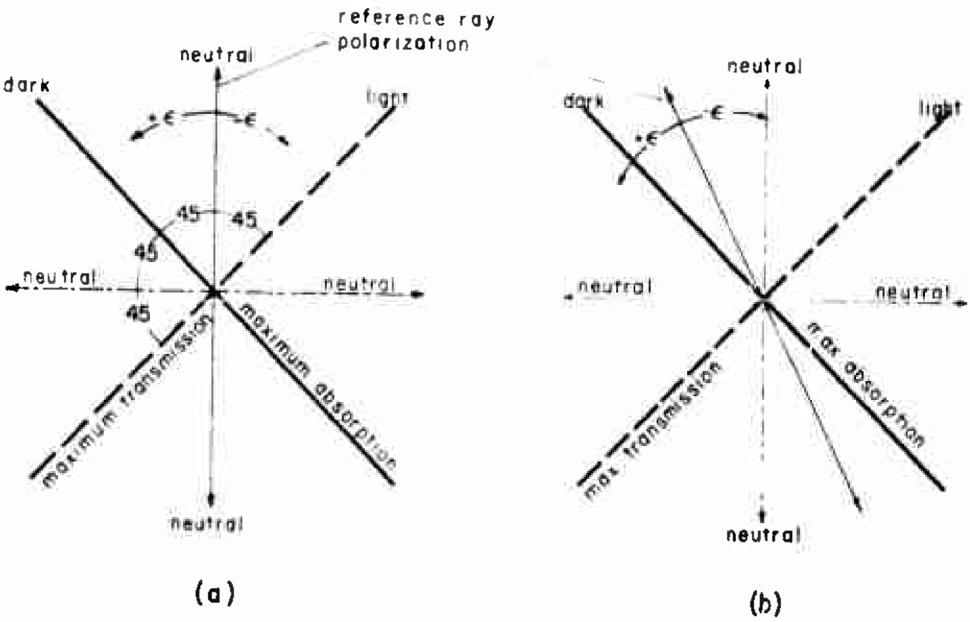


Fig.10 Poloroid sheet and reference ray polarization orientation

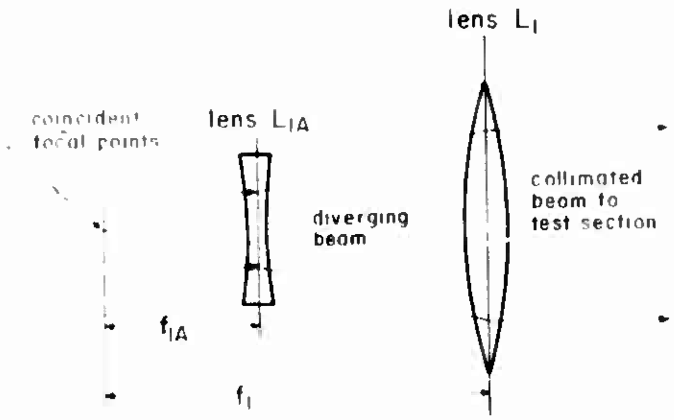


Fig. 11 Divergence of laser beam

a. City gas diffusion flame

b. Candle flame

Fig. 12 Diffusion Flames

Fig 13 AP/PBAA sandwich, 500 psi

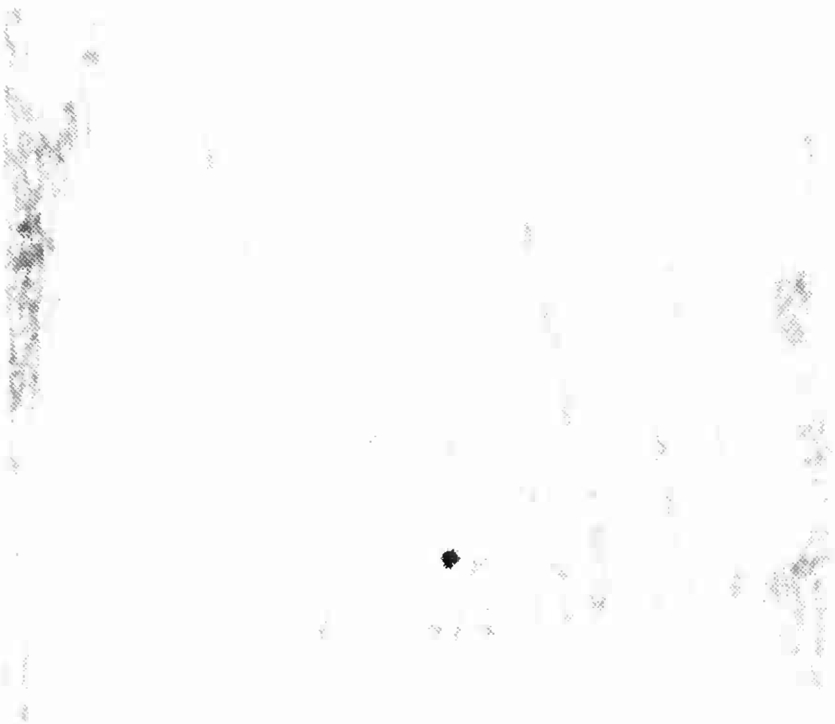


Fig. 14 a AP (single crystal), 500 psi

Fig14 b AP (polycrystalline), 450psi

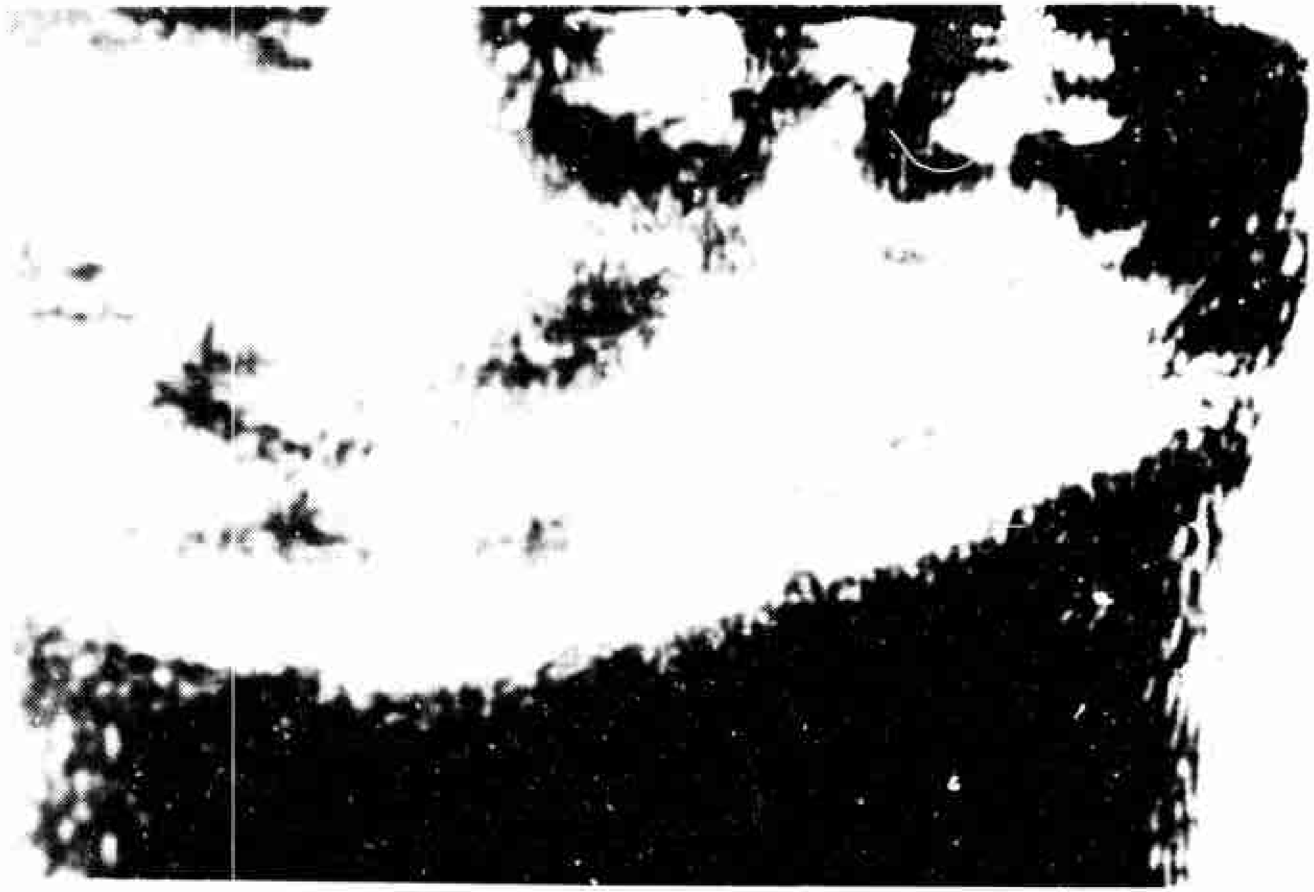


Fig 14 c AP(polycrystalline), 1000 psi

Fig. 14d AP(polycrystalline), 2200psi

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